Boeing Wichita
Human Factors

Visual Performance during Whole Body Vibration

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Boeing
Wichita

Human Capabilities in a Vibration Environment

Human
Factors

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~~Technical Report No. 4~~

6 VISUAL PERFORMANCE
DURING
WHOLE-BODY VIBRATION

10 by Robert J. Teare
and
D.L. Parks

Research Accomplished Under
Office of Naval Research
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21 Report on ~~of~~ Research On
Low Frequency Vibration Effects
On Human Performance

Principal Investigator
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HUMAN FACTORS STAFF

THE BOEING COMPANY
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ABSTRACT

Eight male volunteers were tested in the Boeing vibration facility to determine the effect of whole body vibration on the ability to read counter information. Stimuli consisted of five 5-digit counters varying in height from .05 to 0.2 inches (6 to 24 minutes visual angle at an average viewing distance of 28 inches). Vibration frequencies ranged from 1 to 27 cycles/second at each of four subjective reaction levels.

Both vibration frequency and severity (reaction level) significantly affected two of the five counters. The size of the counter was a factor only if it subtended less than 12 minutes of arc. The most severe area of visual deterioration was from 12 through 23 cps. This was linked to the critical flicker frequency of the eye.

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INTRODUCTION

Of all the senses of man, vision is undoubtedly the most important. Considered anatomically, the eye is the most highly developed of all the sense organs (1). It is capable of transmitting the most elaborate of all sensations and accounts for about 70 percent of all sensory experience. As an information channel, optic nerve fibers are capable of transmitting 430 times more information than are auditory nerve fibers (2). In terms of absolute threshold, sensory comparisons are much more difficult because of differences in stimulus types. However, it is estimated that the skin requires 100 million times more energy than the eye for minimal stimulation (1).

In light of these differential sensitivities and primacies, it is understandable why there is more information available about the eye than for all other senses combined. The visual modality is particularly important as a detection and discrimination device. Since practically all systems involving man require the human component to assimilate and process visual information, the effects of system environments on visual tasks is necessary information.

The study described herein is the fourth in a series of research devoted to the effects of vertical, sinusoidal vibration on human performance. It is devoted to the determination of the effects of vibration on a task involving visual acuity. Other studies, particularly that of Lange and Coermann (3) and Schmitz, Simons and Boettcher (7), have shown that vision is affected by vibration. Of immediate interest to the design engineer is the effect of vibration on specific aspects of visual performance. This document and those which follow will direct their attention to detailed aspects of an operational environment.

METHODOLOGY

Experimental Subjects

Subjects used in the experiment were eight Boeing Airplane Division employees who had participated in earlier vibration research. All subjects were given complete physical examinations as part of a screening process for inclusion in the experimental group. This physical examination included a test of visual acuity. An orthorater was used to obtain acuity for far vision (converted to Snellen notation) and for near vision (converted to Jaeger notation). The acuity measures for each of the eight subjects are presented in Appendix A. All subjects acuity was well within the range of that considered to be "normal" vision.

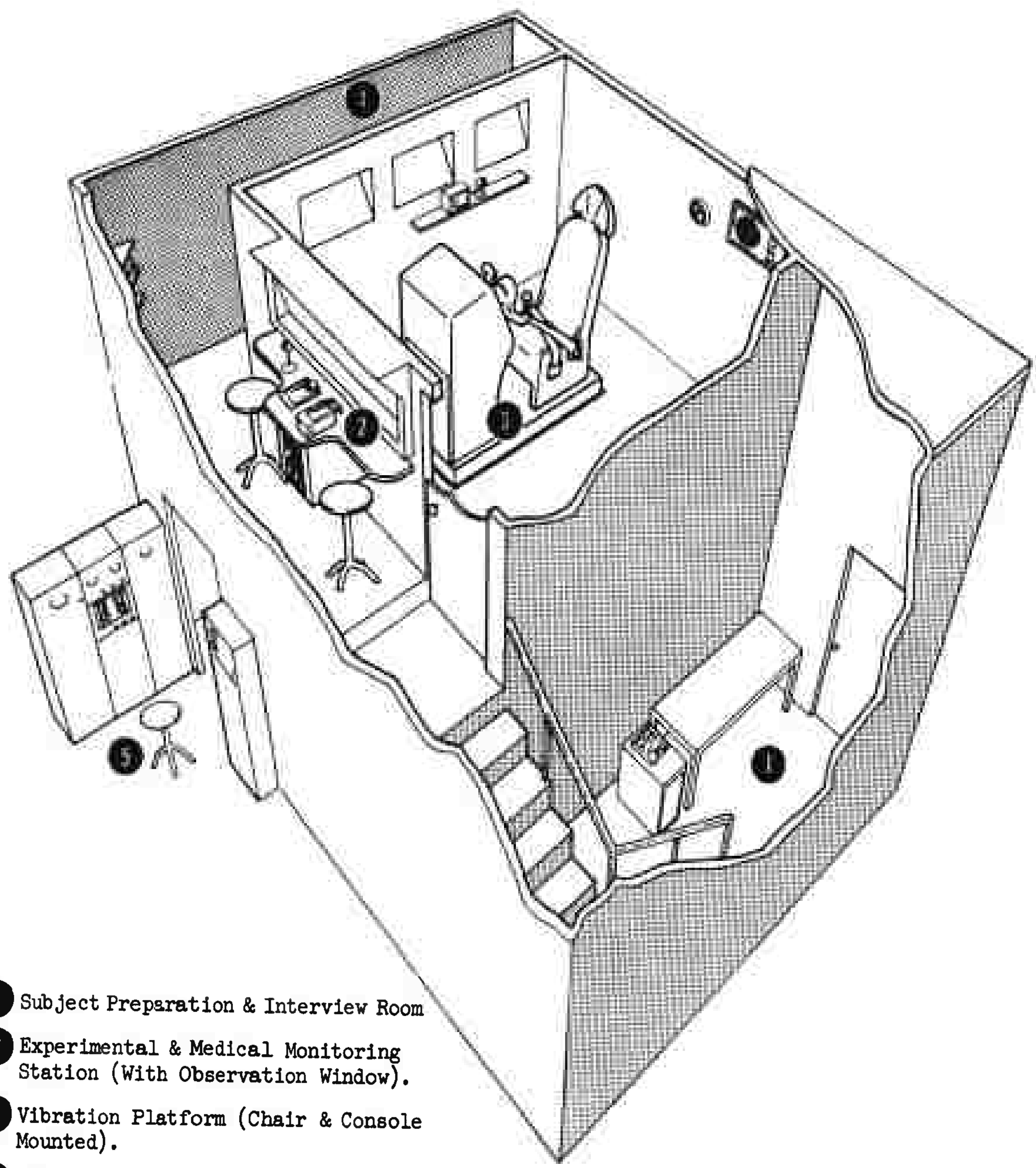
Vibration Apparatus and the Vibration Environment

The Boeing Human Vibration facility was used to provide the vibration environment for this study. This facility is described in detail in a previous document (4). It provided the vertical sinusoidal vibration inputs at the frequencies required for the experiment. An illustration of the facility is presented in Figure 1.

Vibration Conditions

The particular vibration conditions used in this experiment were determined in an earlier document (5). Subjects were tested at four "subjective reaction" levels (definitely perceptible, mildly annoying, extremely annoying, and alarming) at frequencies ranging from 1 through 27 cycles per second (cps). These test condition points are presented in Table 1 in terms of displacement (inches) and acceleration (g). Certain conditions, as indicated in this Table, were omitted because of possible exceedance of physiological limits.

Vibration was controlled by a feedback potentiometer and a signal generator. The first controlled displacement amplitude; the second controlled frequency. The resulting signal was fed into a servo actuated ram which moved the table.



1. Subject Preparation & Interview Room
2. Experimental & Medical Monitoring Station (With Observation Window).
3. Vibration Platform (Chair & Console Mounted).
4. Observation Area (With 3 One-Way Viewing Windows)
5. Equipment Operator's Station (Signal Generation, Feed back, & Monitoring).

FIGURE 1. BOEING HUMAN VIBRATION FACILITY

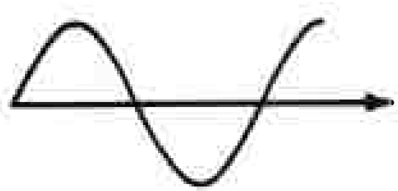
TABLE 1. VIBRATION CONDITIONS USED IN VISION EXPERIMENT

Frequency		1	1.5	2	3	4	5	6	8	10	12	14	16	18	20	23	27
Level 1	DA	.213	.233	.156	.057	.038	.026	.017	.040	.016	.048	.025	.039	.025	.012	.009	.004
	G	.011	.027	.032	.026	.031	.034	.032	.130	.083	.353	.247	.510	.417	.243	.254	.133
Level 2	DA	3.600	2.574	1.477	.942	.370	.172	.148	.113	.055	.082	.056	.068	.053	.035	.019	.012
	G	.184	.296	.302	.433	.303	.220	.273	.371	.281	.604	.565	.894	.871	.711	.515	.436
Level 3	DA	4.877	3.974	2.803						.103	.118	.079	.096	.068	.055	.027	.024
	G	.249	.457	.573						.526	.871	.796	1.260	1.132	1.129	.737	.878
Level 4	DA	5.656	5.792							.145	.155	.110	.105	.085	.074	.034	.026
	G	.289	.666							.740	1.141	1.097	1.368	1.408	1.518	.919	.987

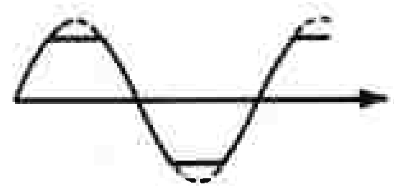
*Controlled vibration input: Displacement double amplitude (2A) in inches; and frequency (F) in cycles per second. Acceleration (G): G = .0511 $F^2$2A. Shaded squares indicate conditions not used in this experiment. Subjective Reaction Levels--Level 1: "Definitely Perceptible", Level 2: "Mildly Annoying", Level 3: "Extremely Annoying", Level 4: "Alarming". The accelerations and amplitudes shown above are taken from the data points (Ref. 5, fig. 5) for which actual values were available, rather than from the smoothed curves describing the subjective levels.

Vibration Fidelity

It had been evident that mechanical and hydraulic properties of the equipment system were introducing distortion into the sine wave output of the vibration table. An analysis of table input versus table output revealed that the distortion was due primarily to table friction. This friction was greatest at the peak of the sine waves and thus resulted in a clipping of the wave form output of the table. This is illustrated in the drawing below.



Wave Input Shape



Displacement Wave Output Shape

This distortion of the wave form resulted in significant third and fifth harmonics being generated in the output. Since the distortion source was essentially constant, it exerted a proportionately greater influence at lower amplitudes than at higher amplitudes.

Distortion also varied as a function of frequency (cps). The relationship with frequency is not a regular one since other factors, i.e. resonant frequency of the table itself and occurence of odd and even harmonics, complicated the frequency picture.

The resulting distortion was analyzed with a describing function (see Boeing document D3-4937, reference 8) and empirically verified on the table. The functional relationship between distortion loss (E_s) and fundamental amplitude (subjective reaction levels 1, 2, 3, and 4) is presented in Figure 2. It can be seen that in the three frequencies chosen (2 cps, 12 cps, and 27 cps) the greatest proportionate distortion occurs at subjective reaction level 1.

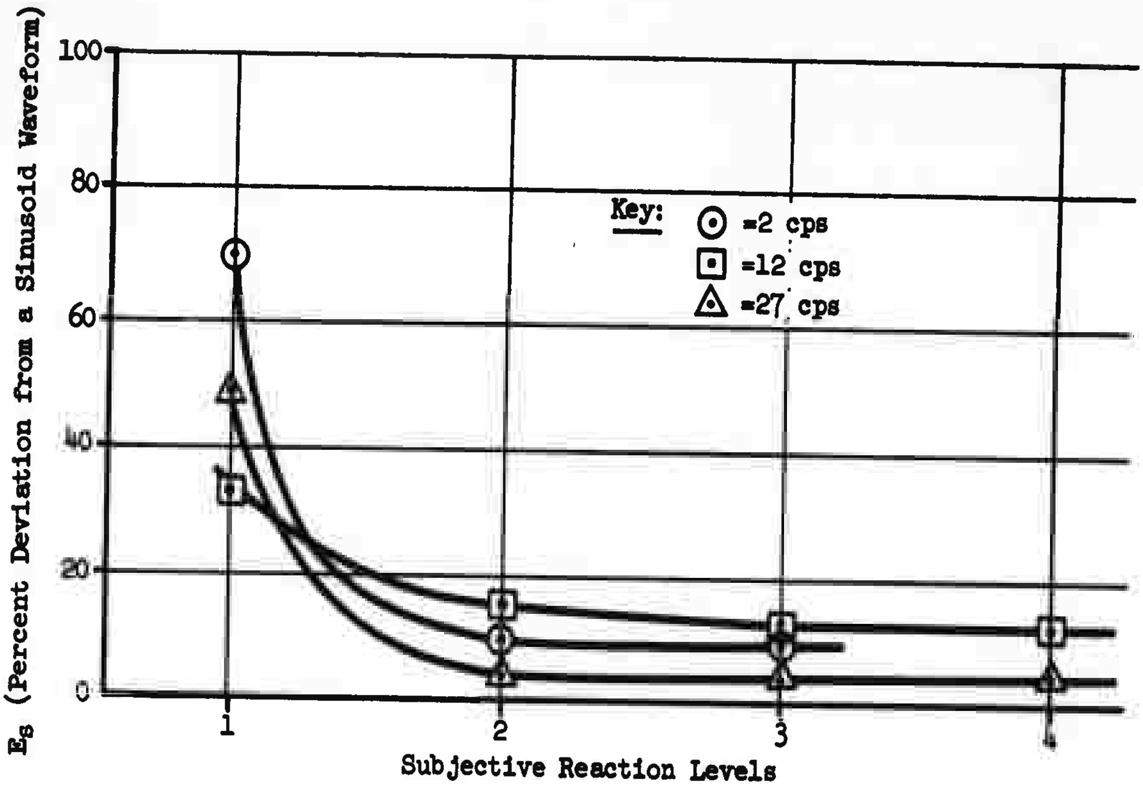


FIGURE 2. DISTORTION CURVES FOR SELECTED FREQUENCIES (AT FOUR REACTION LEVELS)

Test Configuration

An illustration of the test station configuration is shown in Figure 3. As in earlier experiments, a standard aircraft seat was mounted on the platform of the vibration table. Plywood inserts covered with approximately 3/4 inch hard felt were used instead of seat cushions or parachute packs in order to increase the fidelity of vibration transmitted to the subject. A standard military aircraft lap belt secured the subject to the seat.

The display console and controls illustrated in Figures 3 and 4 provided for the range of tasks required in this research program. The entire procedure, in which the counter reading task was a portion, required the subject to use each of the displays on the center display panel (except the CRT display located in the center in line with the dial displays) and a throttle control mounted to the left of the subject. The rudder pedals were used in an isolated task performed at the end of each test session.

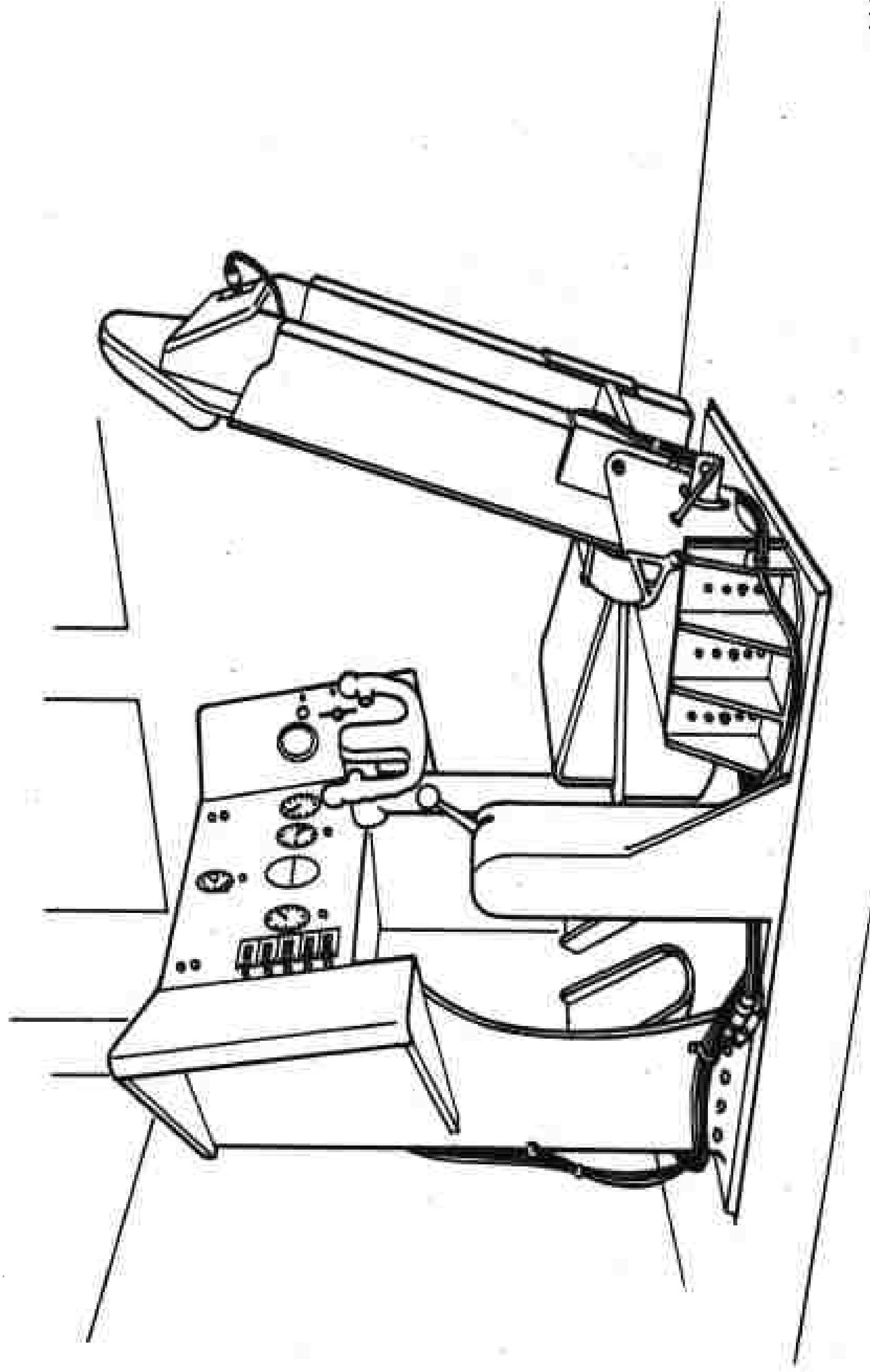


FIGURE 3. TEST STATION CONFIGURATION

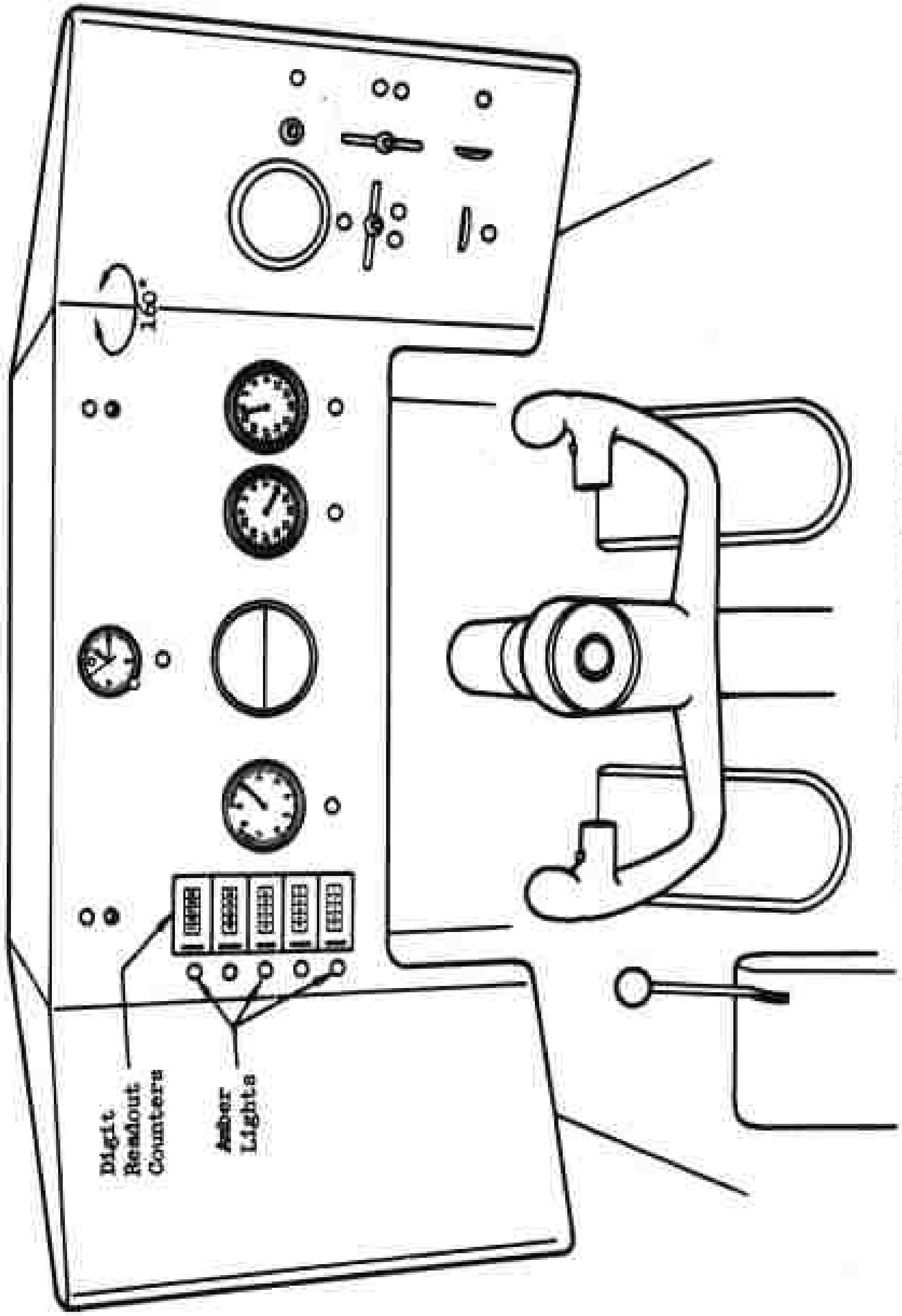


FIGURE 4. INSTRUMENT DISPLAY PANEL

A detailed view of the instrument panel is presented in Figure 4. It should be noted that only part of the instrument configuration and none of the controls were used in collecting the vision data reported here. Only that portion of the panel utilized in the vision study will be described in detail at this time.

Five 5-digit readout counters were arranged in a vertical row in the lower left hand corner of the display panel. The numerals were Leroy style gothic, white on black background, conforming generally to Military Design Standard MS 33558. Numeral height for each counter is presented in Table 2. The counter designations (A through E) were positioned in order from top to bottom. To the left of each counter was an amber light which indicated to the subject when a particular counter was to be read. Average viewing distance was 28 inches.

The light level at the counters, in the plane of the panel, was approximately 32 foot candles.

TABLE 2. COUNTER SPECIFICATIONS

Counter	Height of numbers (in.)	Visual Angle (minutes)
A	.20	24
B	.125	15
C	.10	12
D	.075	9
E	.050	6

Testing Sequence and Procedures

The vision data were gathered as part of a larger task sequence involving movement perception, throttle control movements and clock reading. These procedures and data will not be described in this document. The sequence of events described below includes this other information only to the extent that it aids clarity. On any particular test day, the experimental sequence was as follows:

(1) subject was given a pre-test medical examination and completed a questionnaire indicating diet, previous week's activities, etc.,

(2) electrocardiagram leads (used for medical monitoring) were attached to the subject,

(3) subject donned coveralls, street shoes and light weight leather gloves,

(4) instructions were read to the subject (see Appendix B),

(5) subject was seated in vibration facility and given a quick review of instructions,

(6) a series of no vibration practice runs were given to familiarize the subject with the equipment,

(7) a programmed series of no vibration (control) and vibration (experimental) runs was administered,

(8) subject was debriefed, given a post-test physical and dismissed for the day.

Within the actual testing sequence (step 7), a control (no vibration) run was carried out before and after the vibration conditions were initiated. These no vibration performance data served as reference controls against which vibration performance data <u>for</u> <u>that</u> <u>day</u> were compared. The vibration and task sequences were set up in advance as random events. Eight such task sequences were prepared and were presented by means of a multi-position stepping switch program designed for each.

Each of the five counters was read eight times for a total of 40 counter readings under each vibration condition. Since each counter contained 5 digits, the total number of errors possible under each vibration condition was thus 200. Each of the ten counter numbers (0 through 9) appeared 4 times on each counter for each vibration

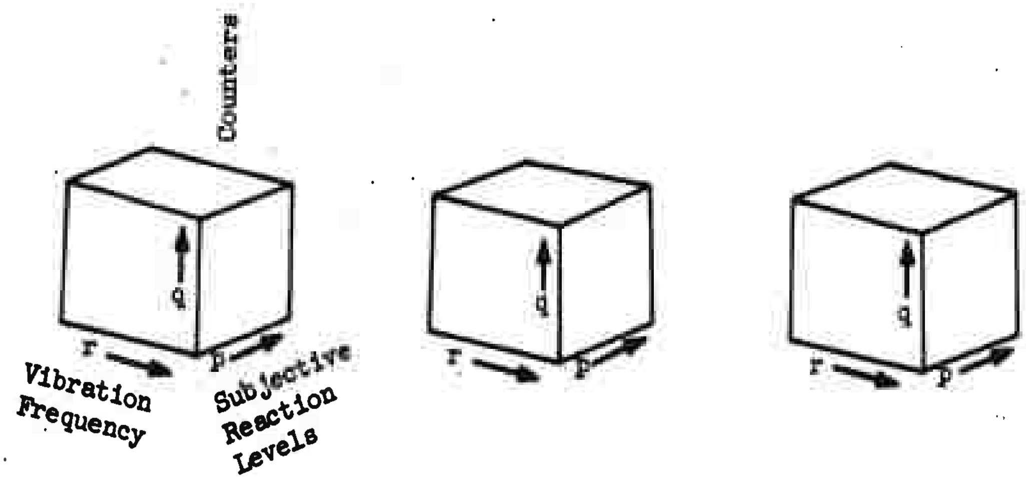
condition. A random order of numbers was selected for the 5 digits in each counter. The relative position of the counter numbers were locked so that the entire counter would rotate one step at a time.

At programmed times throughout the testing sequence, the amber light would flash next to a given counter. The counter positions were read aloud by the subject and recorded on magnetic tape.

Data Analysis

The conditions used in this experiment involved variations in vibration severity (subjective reaction levels), vibration frequency (cps) and counter size. These conditions were varied simultaneously in repeated observations of eight subjects.

These data were cast into a four dimensional analysis of variance (ANOV). The dimensions were: subjective reaction levels (with p levels), counters (with q levels), frequency of vibration in cycles per second (with r levels), and subjects (with s levels). The design was essentially a "p x q x r" factorial repeated over s subjects.



Previous vibration research (6) had indicated the possibility of internal organ damage at frequencies in the 3 - 8 cps range. Because the time required for completing the task sequence exceeded the one minute time exposure used in establishing tolerance limits (6), these frequencies were not used at reaction levels 3 and 4. These omissions are indicated by the shaded areas in Table 1.

Because of these omissions, the data were treated in two separate analyses. The first utilized the entire cps range (1 through 27 cps) at subjective reaction levels 1 and 2. It was a "2 x 5 x 16 x 8" factorial. The second utilized all four reaction levels but used only the frequencies common to all four levels. It was a "4 x 5 x 10 x 8" factorial. The dependent variable analyzed was the difference between the accuracy of a counter read-out under a given vibration condition and the read-out accuracy of that counter established during the no vibration "control" run for that day.

RESULTS

The analysis of variance summary data are presented in Tables 3 and 4. It can be seen from inspection of these Tables that practically all sources of variability in the experiment are statistically significant. This is due, in part, to the form which the analysis has taken. Since all variables are based on repeated measurements, the degrees of freedom, particularly those for the second and third order interactions, are quite large. This reduces in size the value of the F or F' ratio needed for significance. Although resulting in more sensitive tests, it may allow variables which are not of practical significance to achieve statistical significance.

Since the two analyses are based on the same variables and the results are quite similar, they will be discussed together as a unit.

First of all, the main effects (subjective reaction level, counters and frequencies) are all significant sources of variation. As expected, the increase in vibration severity (from level 1 through level 4) was accompanied by almost a linear increase in the number of errors made. These data are presented in Figure 5.

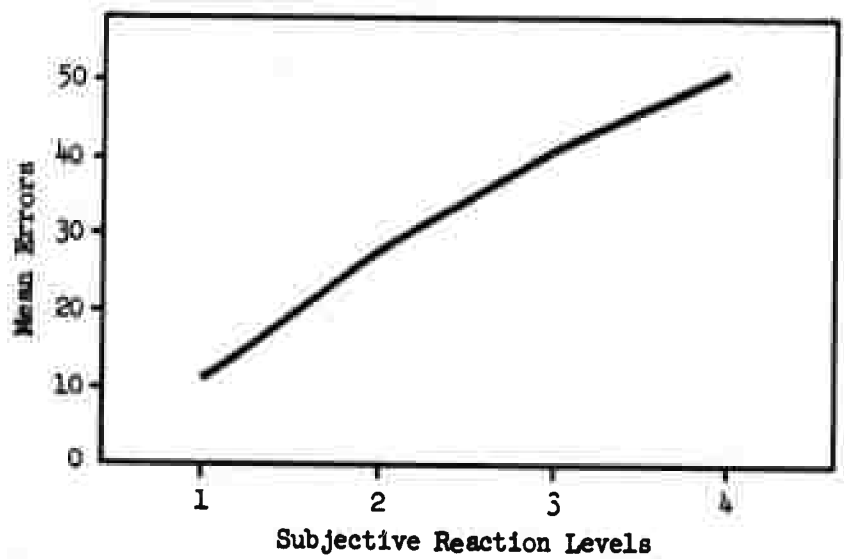


FIGURE 5. MEAN ERRORS (5 COUNTERS) BY LEVEL

TABLE 3. ANALYSIS OF VARIANCE SUMMARY TABLE (ANALYSIS I)
(2 levels [1], 16 frequencies, 5 counters, 8 subjects)

Source of Variability	Sum Squares	df	Mean Squares	F or F'	Signif.
A (levels)	3,694.633	1	3,694.633	99.262	***
B (counters)	31,935.746	4	7,983.936	6.561	*
C (frequencies)	13,442.691	15	896.179	8.385	***
P (subjects)	3,848.660	7	549.808	14.771	***
AB	4,403.363	4	1,100.841	51.704	***
AC	1,146.906	15	76.460	2.250	*
AP	260.551	7	37.221	2.739	*
BC	20,590.477	60	343.175	9.390	***
BP	3,845.949	28	137.355	6.451	***
CP	6,762.039	105	64.400	1.895	***
ABC	1,484.937	60	24.749	1.821	**
ABP	596.148	28	21.291	1.567	*
ACP	3,568.523	105	33.986	2.501	***
BCP	10,662.586	420	25.387	1.868	**
ABCP	5,706.937	420	13.588		

[1] Levels 1 & 2 through all vibration frequencies, (see Table 1).

* $p < .05$
** $p < .01$
*** $p < .001$

TABLE 4. ANALYSIS OF VARIANCE SUMMARY TABLE (ANALYSIS II)
(4 levels, 10 frequencies [1], 5 counters, 8 subjects)

Source of Variability	Sum Squares	df	Mean Squares	F or F'	Signif.
A (levels)	10,188.695	3	3,396.232	33.795	***
B (counters)	103,601.242	4	25,900.310	28.244	***
C (frequencies)	21,044.578	9	2,338.286	18.682	***
P (subjects)	10,751.516	7	1,535.931	12.271	***
AB	6,920.375	12	576.698	7.500	***
AC	2,458.273	27	91.047	1.695	*
AP	1,326.539	21	63.168	1.176	- -
BC	23,369.719	36	649.159	13.700	***
BP	8,826.516	28	315.233	6.653	***
CP	7,885.406	63	125.165	5.260	***
ABC	5,499.375	108	50.920	2.140	***
ABP	4,180.594	84	49.769	2.091	***
ACP	10,153.273	189	53.721	2.257	***
BCP	11,940.695	252	47.384	1.99	***
ABCP	17,992.234	756	23.799		

[1] Vibration frequencies 1, 1-1/2 cps and 10 through 27 cps (see Table 1).

* $p < .05$
** $p < .01$
*** $p < .001$
\- - non-significant

As the Figure indicates, there is a four fold increase in the number of read-out errors as vibration increases from the "definitely perceptible" level to that of "alarming".

Counter size also makes for a decided difference in the accuracy of read-outs. The data (means) for counters are presented below in Figure 6. Plotted on the same graph are the number of errors made for each counter under the "no vibration" control conditions. The fact that counters D and E account for the bulk of the errors is clear. Furthermore, this cannot be explained in terms of the inherent difficulty of the counters since control data indicate that there are no differences in reading errors when vibration is not present.

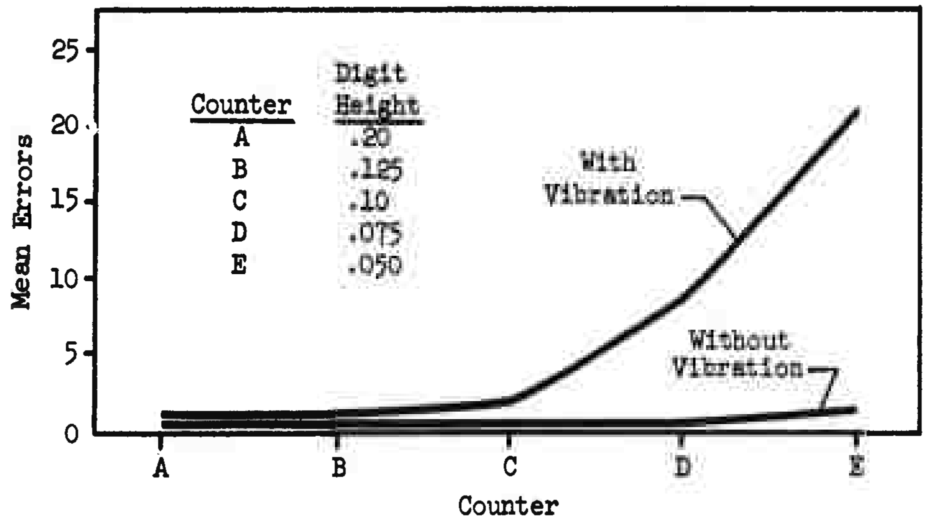


FIGURE 6. VIBRATION AND NO VIBRATION ERRORS FOR EACH COUNTER

Individual differences being what they are, it would be expected that subjects would react to the frequency and severity of vibration in different ways. This is borne out by the data again in the form of second and third order interactions of the subjects with the vibration variables. The significance of "subjects" as a main effect is explained by Figure 7 below. It can be seen that subjects 2 and 4 produce the greatest number of errors under vibration. Subjects 1 and 2 are responsible for the bulk of the errors under the no-vibration conditions.

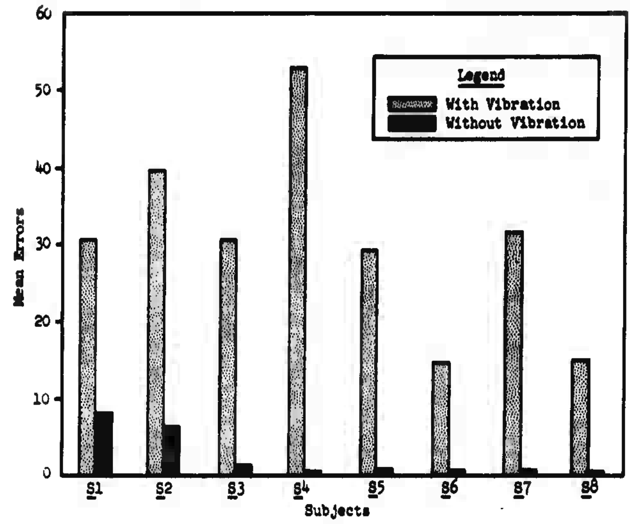


FIGURE 7. MEAN ERRORS MADE BY SUBJECTS

In both analyses I and II there is a significant interaction between severity level (subjective reaction level) and frequency. In essence, this means that the pattern of errors at the various frequencies changes from level to level. Figures 8 and 9 present a plot of the frequency of errors produced at the differing frequency (cps) points. In Figure 8, the data are broken out for each level separately Figure 9 presents these data as a composite curve. Both presentations indicate the trend for errors to increase quite drastically in the 12 through 23 cps range. For the most part, errors remain relatively stable in the low frequency range, particularly at subjective reaction levels 1 and 2. The interaction is probably caused by differences in the curves at low frequency. There is a consistent tendency for errors to begin to decrease sharply at 16 - 18 cps and to continue this decrease to the end of the frequency test spectrum.

Perhaps the most revealing data of all are those which are presented in Figure 10. It is evident from the data plot that the rise in errors for the 12 to 23 cps range is due in large measure to counters D and E. Counters A, B, and C (describing 12 to 24 minutes of arc) are relatively insensitive to vibration throughout the entire range tested. Counter D (9 minutes of arc) is unaffected until the 10 cps point.

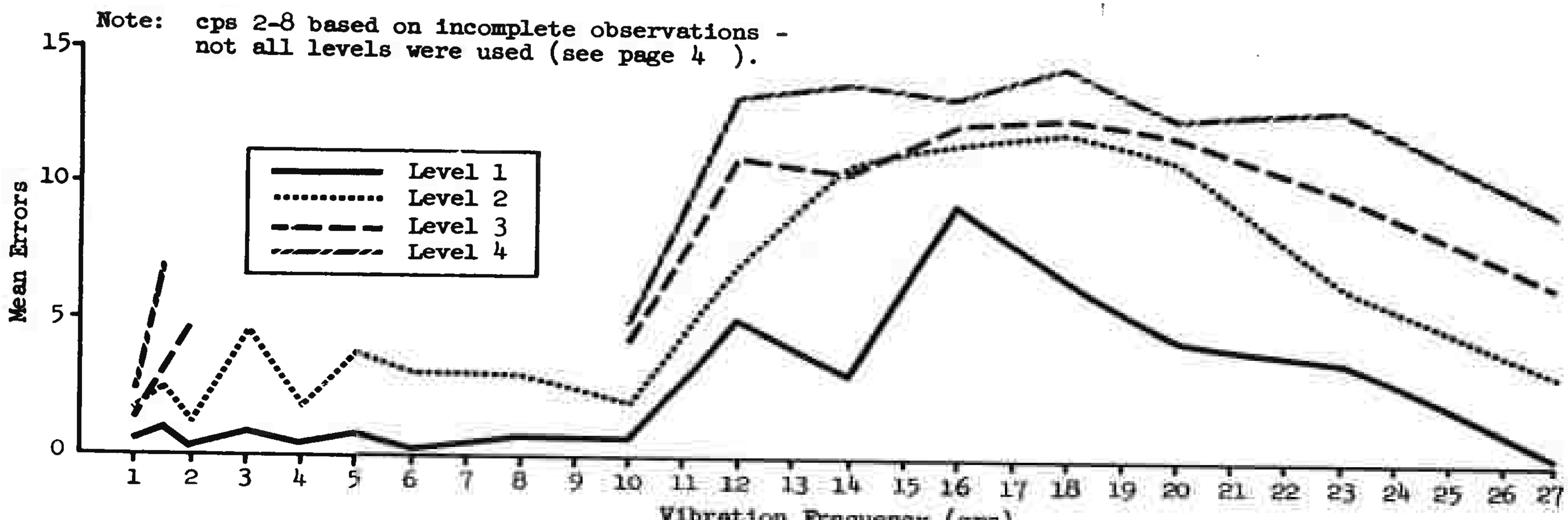


FIGURE 8. MEAN ERRORS (FOR ALL COUNTERS) AT EACH FREQUENCY AND LEVEL

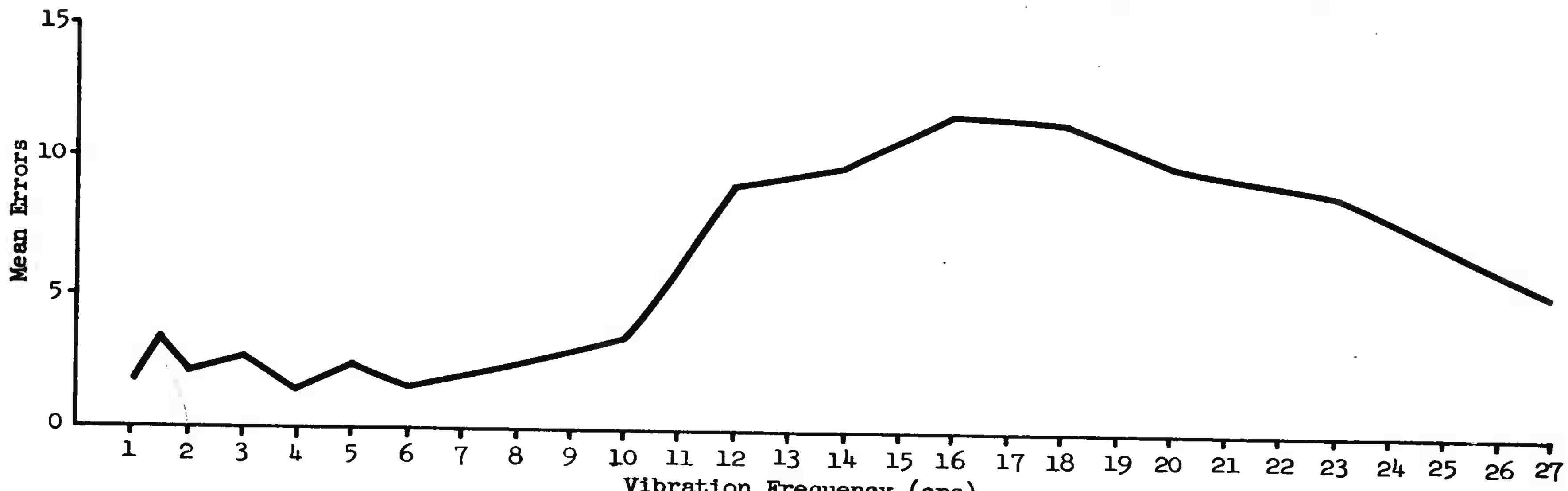


FIGURE 9. MEAN ERRORS (FOR ALL COUNTERS) AT EACH FREQUENCY

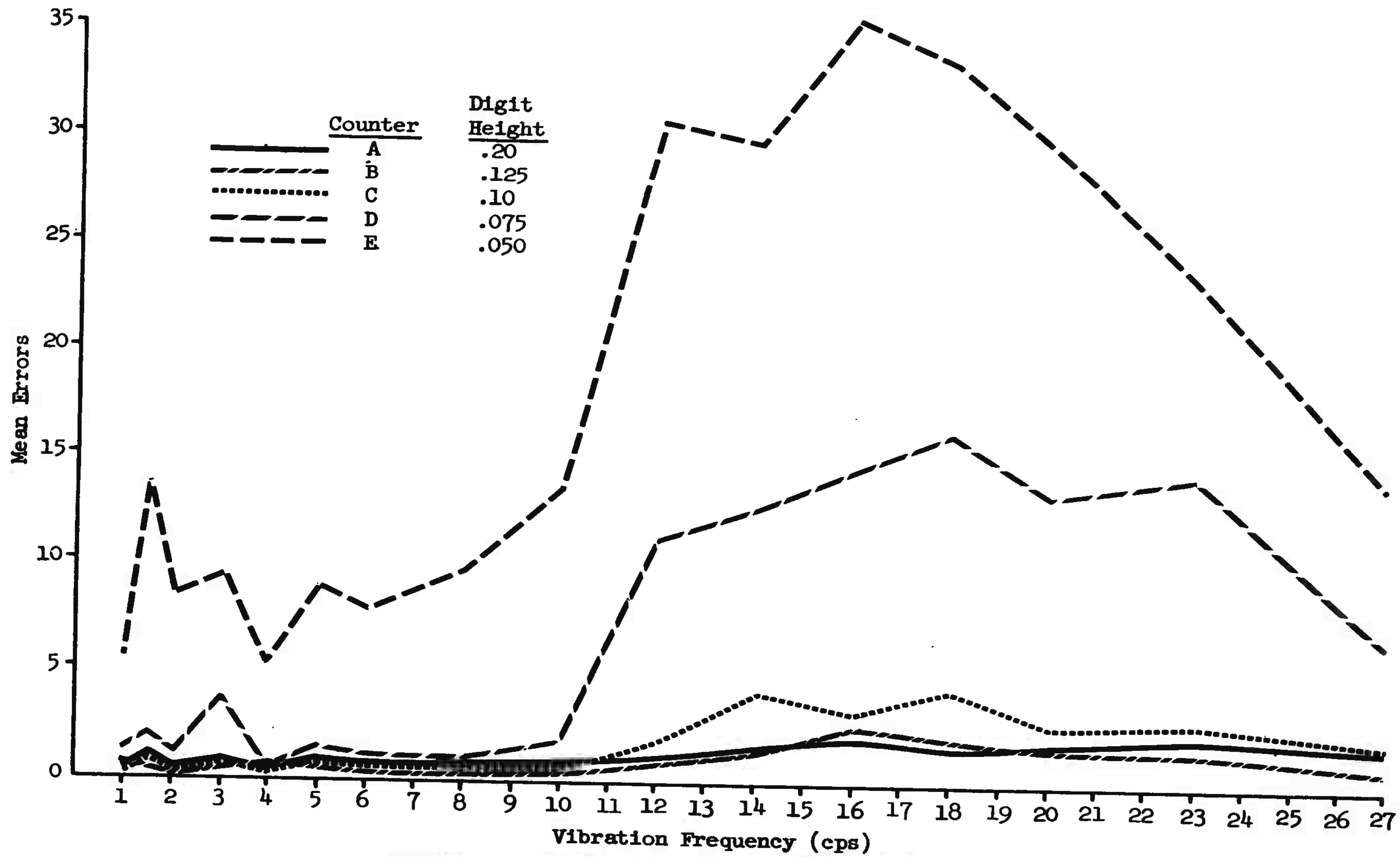


FIGURE 10. MEAN ERROR (BY FREQUENCY) FOR EACH COUNTER

At that point, it becomes increasingly difficult to read and describe the error function noted originally. Counter E (6' arc) is decidedly more difficult to read at all vibration frequencies.

Furthermore, there is a decided tendency for the readability of Counters D and E to be affected by severity level. Figures 11 and 11a present the counter comparisons (vibration vs. no vibration) for each counter and each severity level. Again it is clear that reading errors for each counter essentially remain the same without vibration. Counters D and E become increasingly more difficult to read as severity level increases.

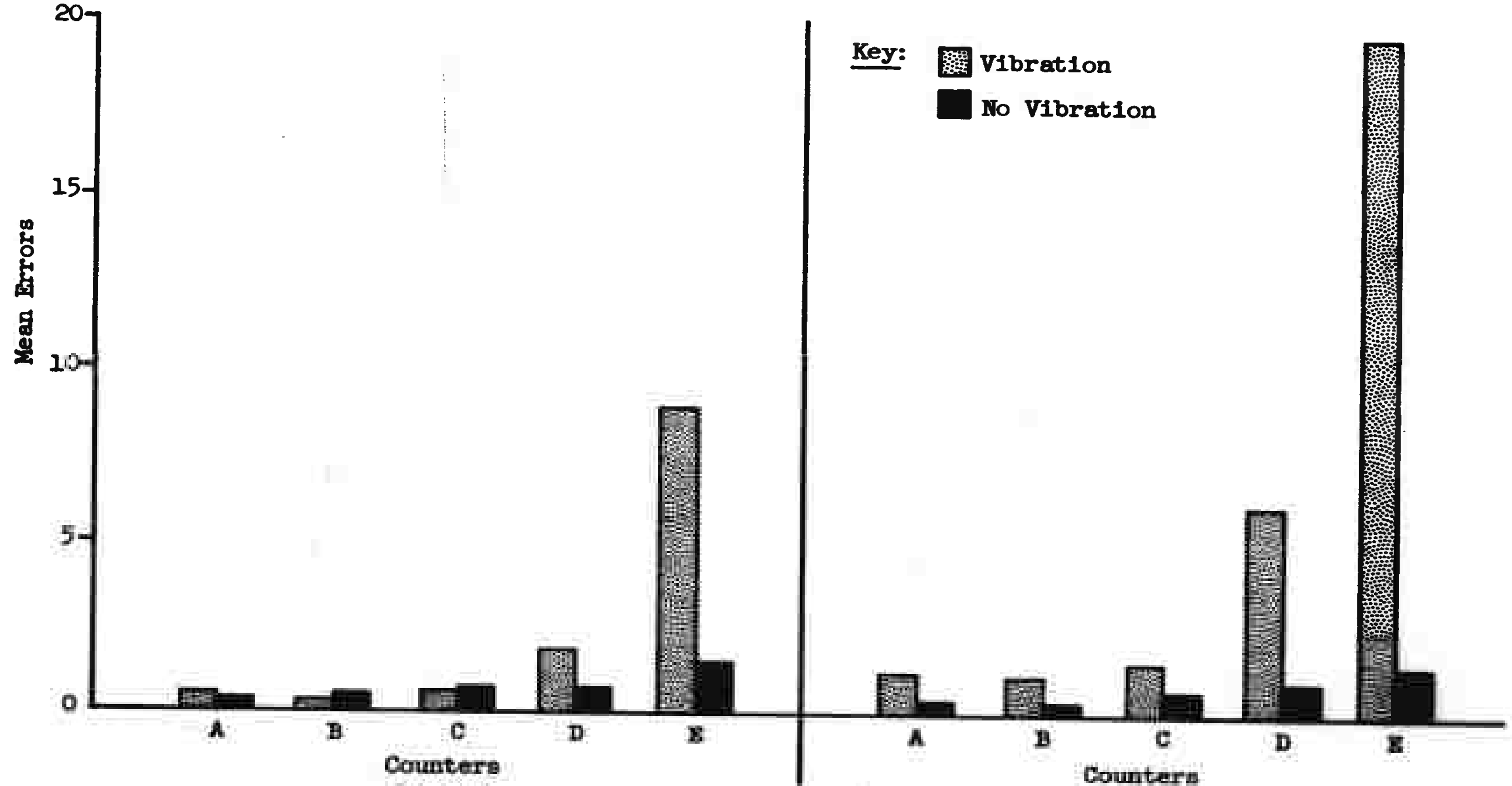


FIGURE 11. COUNTER ERRORS FOR EACH OF THE FOUR SUBJECTIVE REACTION LEVELS

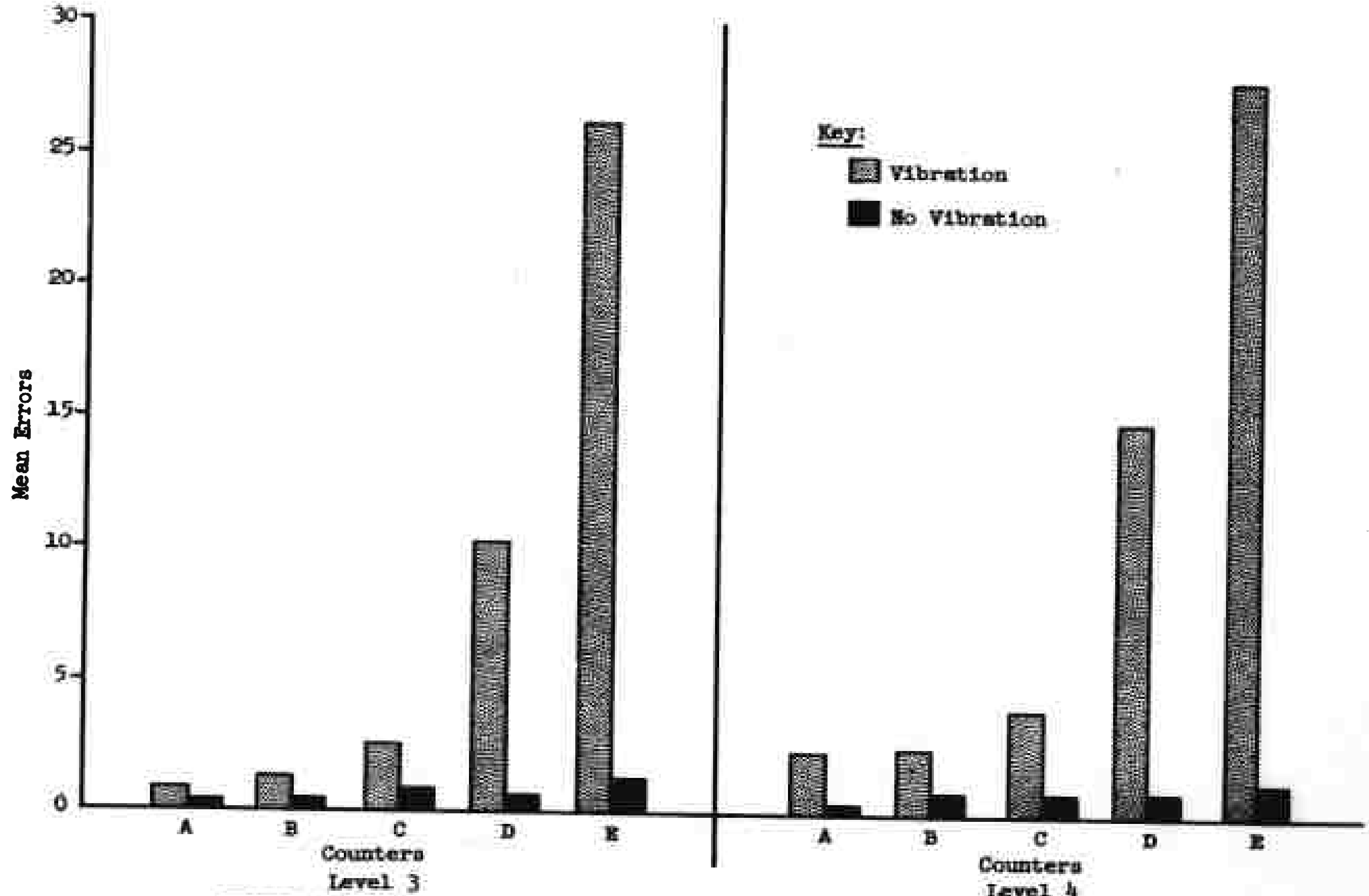


FIGURE 11a. COUNTER ERRORS FOR EACH OF THE FOUR SUBJECTIVE REACTION LEVELS

SUMMARY AND CONCLUSIONS

The data indicates that both vibration frequency and severity (subjective reaction level) affect the readability of dial counter information. This effect was restricted to frequencies above the 12 cps level and was true only if the digit to be read subtended less than 12 minutes of arc at an average viewing distance of 28 inches.

The deterioration of legibility registered sharply at 12 cps might possibly be explained in terms of the critical flicker frequency of the human eye. This occurs somewhere between 8 and 16 cps and the blurring which accompanies it is due to the inability of the brain to reconcile the image. The decrease in errors noted at the tail end of the spectrum may be due to the tendency of the smaller digits forming distinct double images and thus increasing the ease with which they could be read.

There is also a decided possibility that visual acuity was affected by the phase lag between the top of the head and the instrument console. An analysis of data yielded from accelerometers placed at strategic positions in the station, indicated that phase shifting of this type actually occurred during the vibration sequences.

At this point in time, only a preliminary analysis has been made of these data. These will be examined in more detail after careful analysis of table distortion (see page 5) have been completed.

APPENDIX A

VISUAL ACUITY DATA FOR SUBJECTS

VISION ABILITY

Subject No.	Distant	Near
1	R. 20/17 L. 20/17	R. J 1 L. J 1
2	R. 20/17 L. 20/17	R. J 3 L. J 2
3	R. 20/18 L. 20/20	R. J 1 L. J 1
4	R. 20/17 L. 20/17	R. J 1 L. J 1
5	R. 20/17 L. 20/18	R. J 1 L. J 2
6	R. 20/17 L. 20/17	R. J 1 L. J 1
7	R. 20/20 L. 20/20	R. J 1 L. J 1
8	R. 20/17 L. 20/18	R. J 1.2 L. J 1.2

APPENDIX B

INSTRUCTIONS TO SUBJECTS

EXPERIMENT 4
INSTRUCTIONS

The purpose of this experiment is to study effects of vibration on vision and movement perception and to determine whether vibration will affect ability to regulate a control lever.

The performance required is as follows:

(1) Counters - As the light on the left of any counter comes on, you are to read aloud the numbers on the counters.

(2) Movement perception - As the light by the right dial (similar to a heading indicator) lights up, you are to watch for movement of the pointer. Movement will last for one second when it occurs. The verbal report will be "movement" or "no movement" as it appears to you.

(3) Clock read-out - A verbal read-out of time to the nearest second will be required. Time to read will also be recorded.

(4) Lever-Pointer Control - As the dial light to the left of the Cathode-ray tube (CRT) comes on, you are to move the pointer (on the airspeed indicator) to 330 by operating the lever on the left side of the control column. To insure comparable data, you are to grasp the knob in the palm of your hand. The force required to adjust this lever will vary from setting to setting.

(5) Time to complete each task will be recorded in addition to accuracy. The maximum time allotted for counter reading is 5 seconds; for movement and lever-pointer control is 10 seconds.

(6) Sequence of presentation will be random.

Are there any questions?

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